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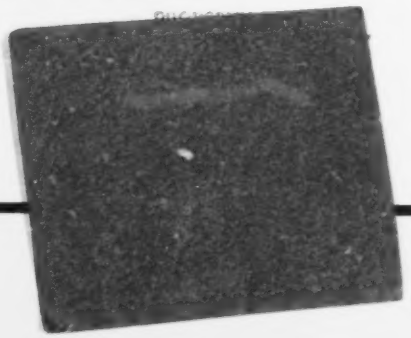

COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE

NATIONAL RESEARCH ON SPACE DEBRIS

SAFETY OF NUCLEAR-POWERED SATELLITES

PROBLEMS OF COLLISIONS OF NUCLEAR-POWERED SOURCES WITH SPACE DEBRIS

Note by the Secretariat

Addendum

1. The Secretary-General addressed a note verbale, dated 19 July 1996, to all Member States, inviting them to provide information on national research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris.

2. The present document contains information provided in replies received from Member States between 7 December 1996 and 6 February 1997.

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REPLIES RECEIVED FROM MEMBER STATES

Germany*

[Original: English]

Germany is closely following the discussions in the space-debris work plan of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS). It has already contributed to these activities *inter alia* through technical presentations and appreciates the information which has so far been compiled. The results of this work process will be of great importance for the definition of future approaches in the field of space debris research and prevention. The following report, which continues the description of German activities as it was provided for the last time in document A/AC.105/619/Add.1 of 1 February 1996, is to be regarded as another contribution to this process.

German space research activities are either conducted on a national footing or are funded under contracts with the European Space Research Technology Centre (ESTEC) and the European Space Operations Centre (ESOC) of the European Space Agency (ESA). The research activities are largely concentrated in (a) the Institute of Flight Mechanics and Space Flight Technology of the Technical University of Braunschweig (IFR/TUBS) and (b) the Research Establishment for Applied Science of Wachtberg-Werthhoven (FGAN). In the following, the main results of research of these institutions during the year 1996 are contained in sections I and II, respectively; section III contains other additional research activities of the Ernst-Mach-Institute in Freiburg and the Battelle-Research-Institute in Eschborn.

Before entering into the description of German research activities, it has to be mentioned that the German Space Agency (DARA) has recently applied for full membership in the Inter-Agency Space Debris Coordination Committee (IADC). During the Steering Group meeting of IADC in October 1996, the formal admission of DARA was proposed to be executed at the next full meeting of IADC, taking place in March 1997 at Darmstadt, Germany, alongside the Second European Conference on Space Debris at ESOC, which is co-sponsored by DARA.

A. Modelling space debris

At IFR/TUBS (Institute of Flight Mechanics and Spaceflight Technology, Technical University of Braunschweig) research work on space debris has been continued.

New features have been implemented in the ESA MASTER[1] Space Debris Model by IFR. The analyst application of the tool now contains also a state-of-the-art meteoroid model.[2] The updated version of the MASTER model is planned to be delivered within the framework of the Second European Conference on Space Debris (Darmstadt, March 1997).

1. Analysis of the space debris collision risk at geosynchronous altitude outside the equatorial plane

Any model concerned with altitudes as high as geosynchronous is limited by the lack of available measured data in this region for objects smaller than 1 m for validation of the model-predicted data. Nevertheless, the comparative analysis[3] of target orbits under the same model assumptions is valid and provides relevant data for future mission design. During the past years, the main efforts in modelling the near-Earth space environment have been concentrating on LEO and the geostationary ring in the equatorial plane (GEO).

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*This reply has been reproduced without formal editing.

Highly inclined orbits at geosynchronous altitudes were of no operational importance in the past. Currently, however, these inclined geosynchronous orbits, IGSOs, are being studied for a number of satellite constellation concepts. In particular, the civil navigation community in Europe is looking at them in the context of a future Global Navigation Satellite System. IGSO satellites in orbits inclined up to 75° would provide adequate regional coverage in an early implementation stage of an eventually global system.

A complete spherical shell at the radius r = 42,164 km ± 1,000 km has been divided into control volumes with Δ r = 25 km, 2° in declination and 10° in right ascension. The MASTER Reference Population as of 1995.0 has been used to render values for the spatial density in these bins. Figure 1 shows the result for a diameter threshold of 1 cm and 1 mm respectively. Trackable objects in GEO are still recognizable as a peak at 0° inclination in the size regime larger than 1 cm. Dominating in both curves, however, are the objects in Molniya type orbits. Smaller fragments stem mainly from break-up events in these highly eccentric orbits. Due to their initial inclination around 63.4°, the rotation of their line of apsides remains small for some of the fragments. This leads to generally higher spatial density values in the northern hemisphere and to a local minimum at around -63° declination.

The impact characteristics, however, vary considerably between target satellites in GEO and in IGSO. Due to the inclined orbit the collision velocity spectrum is shifted to higher values and reaches up to between 4 and 5 km/s compared to the moderate values of down to 500 m/s and less in GEO (see figure 2). Debris objects of millimetre size may carry the same destructive potential in case of a collision with large bodies in IGSO as centimetre size particles do in the current GEO environment. The different impact geometry is also reflected in the encounter direction: azimuth angles (measured in the horizontal plane from the direction of flight) are narrowed down to 30-50° (see figure 3). The elevation is spread ±20° around the average and peak value of 0°.

The orbital lifetime at geosynchronous altitude is usually assumed to be nearly infinite. Even though the orbit is perturbed by the lunisolar gravitational influence, the solar radiation and the asymmetric geopotential, there is no relevant secular change of the orbital parameters. In particular, on GEO the increase in eccentricity is slow and no energy is dissipated. However, long term simulations with the stroboscopic computer code LOPEX,[4] taking into account all relevant perturbations, reveal an abruptly changing behaviour of IGSOs with an inclination of more than about 45°. Figure 4 shows the orbital lifetime of 3,000 objects with randomly generated initial values for inclination, eccentricity, right ascension of the ascending node and argument of perigee. A large number of objects with initial inclinations mainly between 45° and 80° (and the correspondent symmetrical values of i > 90°) decays after as short a time as 30 to 200 years.

Figure 1. Spatial density vs. declination in IGSO

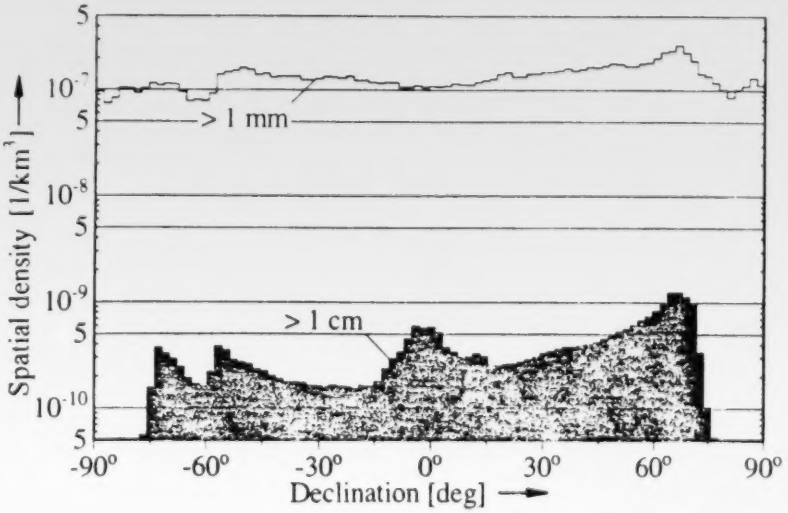


Figure 2. Encounter velocity in IGSO vs. GEO

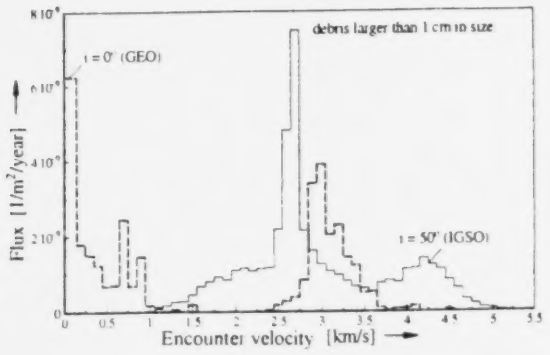


Figure 3. Angular flux distribution in the horizontal plane

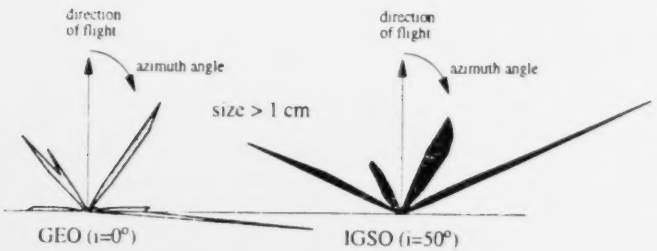
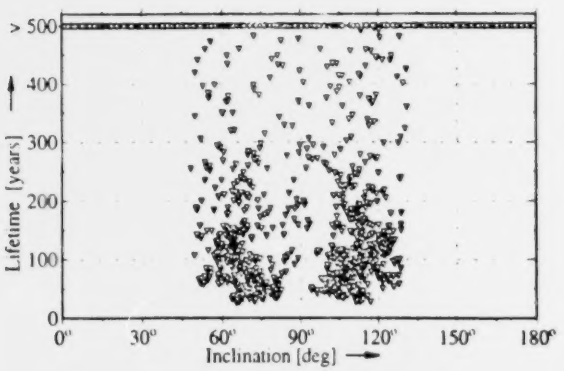


Figure 4. Lifetimes of 3000 randomly generated objects in IGSO (i_0 = 0° ... 180°, e_0 = 10^{-5} ... 10^{-1})



From a debris mitigation point of view, there are pros and cons for the use of IGSOs. They are a potential risk to the existing objects in the geostationary ring, in particular because of their higher relative velocity. Debris clouds from fragmentation events in IGSO and GEO, advantageously, expand rather quickly over a large volume. The orbit parameters of many of these fragments are spread more than in case of LEO break-ups due to the smaller velocity of the parent object. Further simulations on the evolution of debris clouds in this altitude regime will be undertaken in order to better understand the short term flux increase as a function of the break-up location and parameters.

The removal of satellites after the end of their operational lifetime can be optimized by taking advantage of the natural perturbations. Whereas geostationary satellites used to spend the last remaining fuel to leave GEO and reach the highest possible graveyard orbit, IGSO satellites should expend their fuel to change their orbital parameters in a way that leads to a minimum remaining time in the nominal orbit and, if possible, to an early re-entry into the Earth atmosphere. Both the inclination and the eccentricity are potential parameters to tackle. However, due to the small effect of a limited Δv on the inclination, a calculated increase of the eccentricity will be the best method in many cases. The possibility that a particular constellation which was just built up might also result in a reduction of the eccentricity value e shows the need for case-to-case optimization. The required tools are precise orbit propagators and reliable methods for numerical optimization. They are available at the Institute and will be used to develop risk minimization strategies for IGSO operations.

2. Long-term evolution of the debris environment

In most cases the long-term modelling of the orbital debris environment and of debris mitigation measures considering interactive collisions has been performed by the use of simplified approaches. These approaches, which use a certain number of mass and altitude bins in order to describe the debris population, enable a very fast, but in most cases sufficient analysis of future scenarios and of debris mitigation measures in terms of global tendencies.

However, some effects and interactions that may become important, could not be investigated in the past due to the limited resolution of the model. A new semi-deterministic modelling tool (LUCA, Long Term Utility for Collision Analysis) has been developed at IFR TUBS that allows a more detailed analysis of future scenarios. This code no longer uses discrete mass and altitude bins for describing a population and its evolution with time but it uses sample objects (approximately 10 % of the population). These objects are propagated individually and the resulting collision probabilities are recalculated within discrete time steps. This method takes into account changes of the properties of the population in the future, while the previous method determines the future collision rate based on the object number changes only, not on the changes of the orbital distribution.

Within a first evaluation, the results of the new high-resolution and computer-time-consuming analysis tool (LUCA) are compared to the existing low-resolution but fast analytical model (CHAINEE). For this purpose objects > 1 cm at LEO altitudes < 2,000 km have been considered. The comparison underlines that CHAINEE gives adequate results within its range of applicability, but for a number of scenarios the resolution of this model does not reflect all effects. From figure 5 it can be seen that for a relatively simple scenario , i.e. assuming a constant growth rate of the basic population of 1.7 % for the next 100 years, the results for the altitude-averaged numbers of objects > 1 cm as a function of time are similar for both simulations.

But the new tool enables a more detailed look at the evolution of the population with time. For the same scenario as defined above, the altitude dependency can now be obtained as given in figure 6 for two Monte-Carlo runs of LUCA (the curve given in figure 5 represents the trend obtained by averaging over a large number of Monte-Carlo runs). It can be seen in this example that the population growth triggered by collisions can vary randomly. This is due to the relatively low collision rates expected for the next decades.

It also can be seen that in some altitude regions there will be a population growth which is much higher than the overall growth according to figure 5.

The high-resolution analysis of future scenarios including also mitigation measures is ongoing. The results will possibly lead to a better understanding of the dynamic of future population growth and of the effectiveness of debris mitigation.

Figure 5. Comparison of the programs CHAINEE and LUCA assuming a constant growth rate of the population below 2,000 km of 1.7 % for 100 years (averaged curves given)

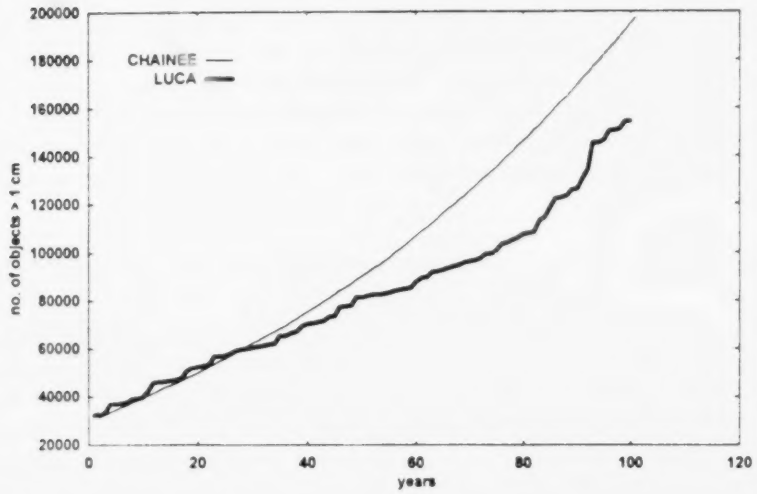
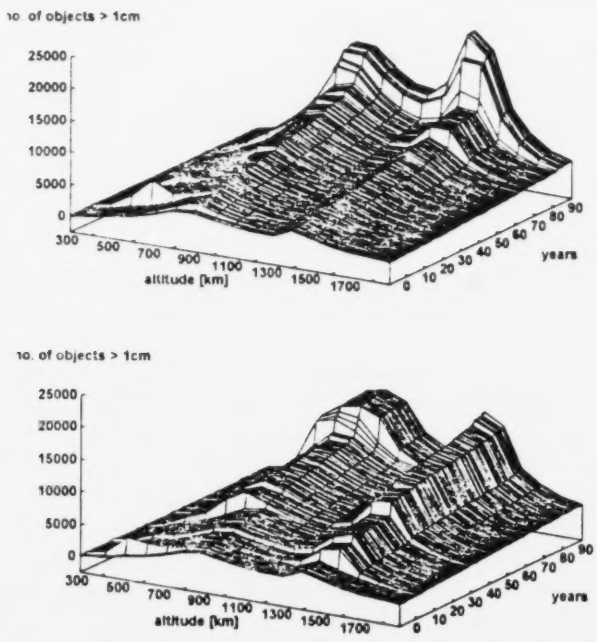


Figure 6. The number of objects > 1 cm per 100-km-altitude shell as a function of time (LUCA simulationMonte-Carlo runs under the conditions as of Figure 5)



B. Radar observations of space debris and meteoroids

Space-debris-related studies at the Research Institute for High Frequency Physics (FHP) in the Research Establishment for Applied Science (FGAN) are aiming primarily at the investigation and development of radar techniques and analysis methods to detect, classify and identify man-made space objects as well as natural meteoroids. Radar data of selected space debris are gained in the tracking mode of operation using the Tracking and Imaging Radar system. From these data the physical properties are derived like size, shape, dimensions, intrinsic motion, mass, orbit, and orbital lifetime. The space debris population density is derived from radar observations of defined space volumes in the beam-park mode of operation. Assessments for the meteor rate during meteor storms are gained from radar measurements where the antenna points perpendicular to the expected meteor stream (beam-park mode of operation with compensation of the Earth rotation). Space-debris flux and meteoroid influx are essential for validation of space-debris environmental models. The activities in 1996 were mainly funded by ESA/ESOC.

The Tracking and Imaging Radar (TIRA) system of FGAN-FHP is primarily used to investigate methods and techniques for classification and identification of spacecraft and aircraft. To a certain extend TIRA is additionally used to gain radar data of space debris and meteoroids.[5,6,7] For that, mainly three modes of operation were developed: a tracking mode of operation to measure selected objects in low Earth orbits (LEO), in geosynchronous orbits (GSO), and in geostationary transfer orbits (GTO). Secondly, a beam-park mode of operation to collect data on the population density of man made space objects in defined space volumes. Thirdly, a beam-park mode of operation with compensation of the Earth rotation to get information on the meteoroid influx during major meteor stream activities.

The TIRA system consists of a narrow-band tracking radar and a high resolution imaging radar. Both radars are supported from a 34-m parabolic antenna. Methods and algorithms have been developed to analyse narrow-band radar signatures, to compute radar images from high-resolution radar data, and to estimate physical properties of space debris like size, shape, dimensions, intrinsic motion, mass, orbit and orbital lifetime. These methods and techniques need further improvement and refinement to cope with mid-size space debris (size 1-50 cm) and meteoroids.

1. Radar observations

In 1996, the space-debris-related research at FGAN-FHP was conducted within the framework of an ESA study (ESA/ESOC Contract, 2/95 3/98). The purpose of this study is to enhance the detection performance of the existing FGAN TIRA system. One of the main objectives is detection and tracking of mid-size space debris (size 1-50 cm) in LEO. The information will be used to validate and improve current environmental models. Within this ESA study all necessary hardware upgrades to enhance the detection performance of the TIRA tracking radar were carried out. Measurements of small radar-calibration satellites revealed that the L-band radar can now observe space debris of 1.7 cm size in the 800 km range.

In 1995, activities were started to further improve the performance to detect 1-50 cm objects with bistatic radar experiments. The close location of the world's largest steerable radio telescope (100 m aperture diameter) at Bad-Münstereifel-Effelsberg, operated by the Max-Planck-Institute for Radio Astronomy (MPIfR), Bonn, and of FGAN-FHP's powerful TIRA system is unique in Europe, and offers promising conditions for cooperative observations of small objects at high ranges. Therefore, within the framework of the above-mentioned ESA study and assisted by DARA, FGAN-FHP proposed to the Directorate of MPIfR a 24-hour cooperative beam-park experiment to collect space-debris radar data for validation of ESA's MASTER model. On 25 November 1996, this COBEAM-1/96 experiment was successfully carried out and 150 GByte radar data were collected. Analysis of the accompanying calibration experiments showed that the 100-m-telescope should have been capable of detecting in the 800-km range objects of <1 cm size.

A major meteor stream activity of the Leonids in November 1999, for which NASA predicts an increase in the background flux by a factor of 10,000-30,000, can cause hazards to operational satellites. On 17 November 1996, FGAN-FHP tested observation strategies for the TIRA system. First analysis showed detections of underdense and overdense ionized meteoroid trails. The collected data will be used to improve the experimental set-up and to assist the development of algorithms for the estimation of the meteoroid influx.

2. Re-entry predictions of high-risk space objects

The objective of this activity is to provide the Federal Minister of the Interior during re-entry of high-risk space objects with reliable predictions of re-entry windows (time and ground track), estimates of the object's attitude and risk assessments. Within cooperation agreements FGAN-FHP provides ESA/ESOC tracking radar data for high-risk space objects to support European re-entry predictions.

C. Other research activities

Most of the investigations of the past year in the field of hypervelocity impact simulation have been continued. They were funded by ESA and industry.

Some tests with light gas guns at the Ernst-Mach-Institut (EMI) have been performed for shield material and configuration screening of the European COLUMBUS element for the International Space Station (ISS). Also, the investigations of the hypervelocity impact effects on pressurized vessels are still going on in order to come to better statistically verified results. The more critical effect of pressurization of vessels has been confirmed by the test results. A consequence of the investigations is a reinforcement of the space debris and meteroid impact shielding for the space station elements.

Other tests at EMI were provided for the investigation of the debris impact behaviour of thermal protection systems (TPS) of re-entry vehicles. Subjects of the investigations were none-ablative materials (fibre-reinforced ceramics), ablative materials, flexible (FEI) and multilayer insolations (MLI) as well as carbon-fibre-reinforced plastic (CFRP) plates and sandwich panels. The terminal ballistic efficiency of CFRP plates and sandwich panels is better than for those made of aluminium. MLI-packages in front of aluminium targets were very effective due to multishock fragmentation. The impact resistance of carbon-carbon materials is comparable with aluminium; however, they have some brittle features (spall effects).

The objectives of the development of the shaped charge techniques for the launching of hypervelocity projectiles at the Battelle Research Institute have been achieved by reproducible results for normal and oblique impacts at velocities above 11 km/s with projectile masses of about 1 gram.

The evaluation of the hypervelocity impact tests performed at the end of 1995 at TDW (Gesellschaft für verteidigungstechnische Wirksysteme mbH) by the so-called cavity charge technique has been finished. The conclusion of the impact testing with superfast jets with tip velocities in the range of 25 km/s is that there is uncertainty in the determination of projectile mass and in the state equation of the jet tip, so that the impact phenomena is certainly quite different to the other methods of debris impact simulation. Further investigations would be required to follow this technique.

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